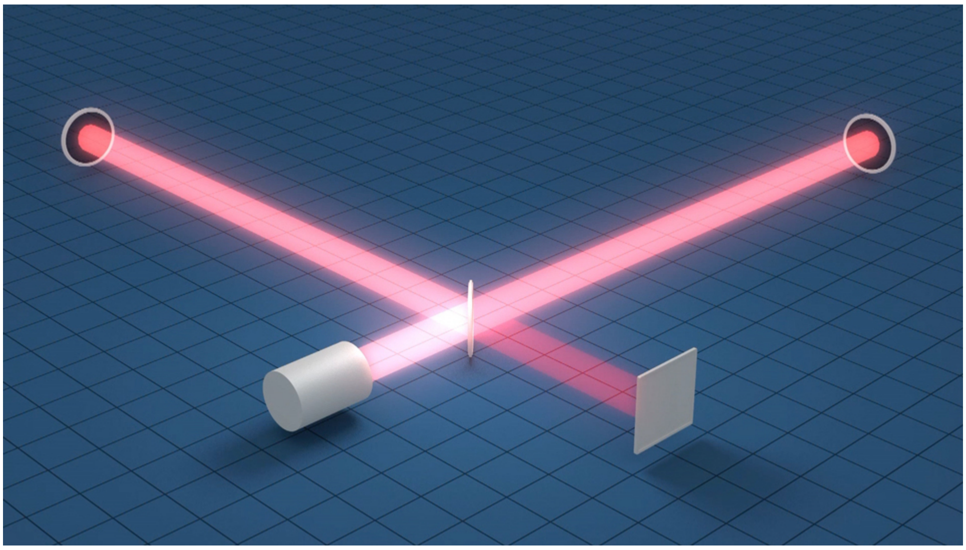

Interferometry

Module: Advanced Practical Physics
Year 2 Teaching Labs
Uncertainty, Choice, Honesty

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Imperial College London

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Previous versions by:
Helder Crespo, Theo Gatward,
David Colling, Alie Craplet, and many others

Contents

1 Introduction

Welcome to the interferometry lab! In this lab, you have the opportunity to build your own high-precision instrument using research-grade components, and get to grips with very powerful principles and techniques which are widely applied in modern research: from gravitational wave detection at LIGO and atomic spectroscopy enabling the study of exoplanents and stellar plasmas in the Imperial College Spectroscopy Lab, to the Atom Interferometer Observatory and Network (AION) in High Energy Physics here at Imperial.

As you progress through the experiment, the lab script will become far less prescriptive and offer you suggestions and chances for open-ended investigation, rather than giving precise instructions. In this lab, you will be assessed on the quality of what you manage to achieve, rather than on how many tasks you have completed. **Therefore, it is better to complete some of the investigations to a high standard than all of them to a lower one.**

In a similar vein, you should take the time to understand the theory and explore the consequences of it using the simulations, rather than merely rushing through data collection. **The codes used for the simulations and data analysis are relatively convoluted and it is important for you to understand how they work**. This will also pay off in the later parts of the experiment, where the data analysis and underlying theory are more complex.

Finally, we have collated some miscellaneous advice from students of previous years that they thought helpful to pass on:

- Interact with demonstrators; they are more than happy to talk to you and help answer your questions.
- Take a couple of breaks in each lab session it is impossible to concentrate for three hours at a time.
- Record, in as much detail as possible, the **choices** you make during the experiment in your lab book; it will help you later in deciding what to investigate in more detail.
- It is useful to come up with a naming system for the interferogram scans you take.

- Prioritise experimental work while in the lab; simulations and data analysis can be done at home to optimise your time using the equipment.

1.1 Key health and safety issues

- This experiment involves lasers. Do not point lasers towards your or any other persons eyes.
- The mercury lamp emits UV as well as visible light, so you **must** wear UV protective goggles when the lamp is on.
- The mercury lamps become hot; take care not to burn yourself when handling them.
- Turn off all light sources and the power to the controller board at the end of each session.

1.2 Objectives of this lab

The aims of the experiment are:

1. To understand the operation of a Michelson interferometer as a spectrometer;
2. To be able to construct, align and operate a Michelson interferometer;
3. To record interferograms using sources with a variety of spectral compositions and different levels of spatial coherence;
4. To simulate the interferogram of a given source and recognise the benefits of doing so in informing what signal to expect and how to conduct data collection;
5. To use these interferograms to describe the spectra of the sources quantitatively;
6. To use a known monochromatic source to correct errors in the scan step and greatly improve the resolution of the instrument.

1.3 Reminder: Second year lab objectives

1. Keep an accurate record of your work.
2. Plan and undertake an experimental measurement and analysis, justifying the choices you make.
3. Assign meaningful uncertainty to an experimental measurement.
4. Appropriately combine and present experimental errors using the error propagation formula.
5. Communicate your results in a well-organised, concise, and accurate manner and use references appropriately.
6. Explain and debate your work with others.

1.4 Indicative schedule

We will begin with a formative session in which you will familiarise yourself with the various optical and optomechanical components in your experimental toolbox, and build and align a basic interferometer using a green laser as a source. You will then directly observe the resulting interference pattern on a white card to see how the **spatial** characteristics of the pattern depend on the source and on the alignment of the mirrors, which is followed by basic data acquisition. Over the following weeks you will be studying sources with increasingly broader and more complex spectral content and with much reduced spatial coherence compared to the highly coherent laser. This means very careful geometric alignment of the interferometer (more on this later on) is vital for obtaining high quality interferograms from such sources. Importantly, you will appreciate that each new interferometer configuration or source can build upon the previous one, so you will not be starting from scratch every time you change your source. The indicative schedule is:

- Week 1: Introduction; formative session focused on producing various types of spatial fringes; basic interferogram measurement with a laser
- Week 2: Study of white and blue LEDs
- Week 3: Study of a mercury (Hg) spectral lamp
- Week 4: Exploration - refine/revisit a previous measurement **or** think of a new one
- Week 5: Submission of four-page report and reflective log (no lab this week)

1.5 How you will be assessed

You will be assessed through:

1. Lab-book sign off in Weeks 2, 3, 4
2. Submission of a four-page lab report in Week 5
3. Completion of a reflective log after submission of the report by end of Week 5

Details on points 1, 2, and 3 are covered on the course Blackboard site. In Section 9 you will find more information on the four-page report related to the measurements and experiments you will be completing. Remember, you can start to think about (and even start writing) your report in the 3rd week of the cycle, so that you have time in the 4th week to collect 'good' data to write about.

1.6 The role of the demonstrators

The demonstrators in the lab are there to support you and give you direct feedback on your work during the lab session. The only assessment during the lab is that you are using your lab book appropriately. This assessment is deliberately light-touch as we want you to take responsibility for your lab book, now that you are in second year. Keeping accurate, descriptive and complete records of your work is a key scientific skill. The demonstrators in the lab will **not** be the ones marking your report − this replicates the blind peer-review process that professional scientists have to go through to get their research published. Therefore, you will get feedback from multiple different people during the session. It is your responsibility to evaluate the variety of feedback that you receive and make decisions based on what you think is best for you and your work.

2 The Michelson Interferometer

2.1 Structure of the Michelson Interferometer

The basic layout of a Michelson interferometer is shown in Figure 1 below. The Michelson interferometer is a division-of-amplitude interferometer. Light is emitted from the source and is split into two beams by a partially-silvered mirror (beamsplitter). The reflected beam (A) travels to a mirror (M1), and the transmitted beam (B) travels to another mirror (M2). Both beams are reflected at their respective mirrors, and upon returning undergo a partial reflection and recombination at the beamsplitter. Adjusting the tilt of M2 along the vertical (as shown in the figure) and horizontal axes enables overlapping of the reflections from M1 and M2 at the plane of the detector (or screen) and fine geometric alignment of the interferometer. Beam splitting and recombination can also be performed with a beamsplitter cube, as used in our lab. This beamsplitter exploits the phenomenon of frustrated total internal reflection to produce the transmitted and reflected beams, but this does not affect the analysis below.

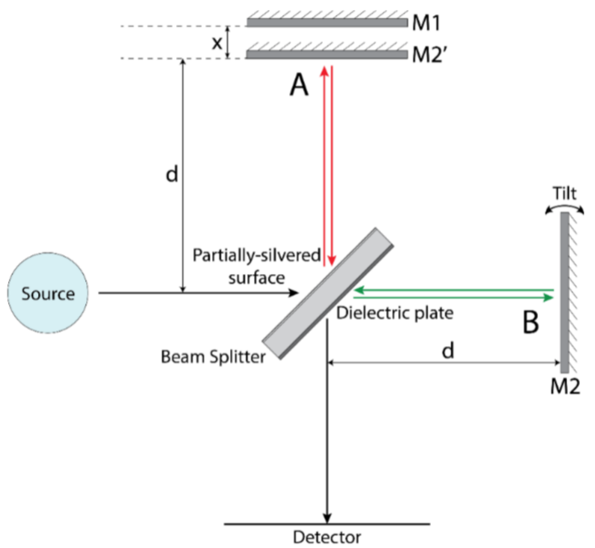


Figure 1: A diagram of the Michelson interferometer setup.

Consider monochromatic plane waves (of wavelength λ and uniform wavevector $\mathbf{k}$) emitted from the source. Plane waves recombining at the beamsplitter will interfere, and the type of interference will be determined by the path difference between the two beams. If the distance from the beamsplitter to M1 is exactly the same as the distance from the beamsplitter to mirror M2, then we may expect these two beams to constructively interfere giving a bright plane wave output. Alternatively, if the distances travelled by beams A and B differ by exactly $\frac{\lambda}{2}$ we might expect the two beams to destructively interfere, leading to no light being incident on the detector. The Michelson interferometer is therefore an extraordinarily precise ruler: moving mirror M1 or mirror M2 by a fraction of a wavelength produces either a bright fringe or a dark fringe at the detector

In the above discussion, we neglected the properties of the beamsplitter substrate, which is typically a dielectric (e.g. glass). This causes a phase difference between the two beams, since the transmitted beam crosses the substrate twice, which is more important for broadband light due to the dependence of the refractive index on wavelength (also known as dispersion). In some cases, a second glass plate with the same thickness as the beamsplitter (the so-called compensating plate) can be inserted in the reflected beam arm to obtain the same dispersion in both arms. In our case, we simply use a cube beamsplitter to obtain a more symmetric splitting in both amplitude and phase. In general, there will always be a wavelength-dependent phase difference between transmitted and reflected beams, but this phase difference is constant and will not affect the use of the interferometer as a spectrometer.

2.2 Types of Visible Fringes

The nature of the fringes seen when looking into a Michelson interferometer depends on how you set up the instrument and on how you illuminate it. On one hand, the two end mirrors (M1 and M2) may or may not be exactly at right angles to each other, and you may either send collimated light into it (parallel rays coming from infinity, i.e. plane waves), diverging light (spherical waves), or you may use an extended source.

2.2.1 Haidinger fringes

Consider first using an **extended source** and setting the mirrors at right angles to each other. A convenient construction, sketched in Figure 2, makes drawing ray diagrams easier. Referring first to Figure 1, looking into the instrument, mirror M2 appears to be at the position of M2′.

If the arms differ in length by t (please note that t denotes a distance here, and not a time delay), an observer imagines seeing the light originating from an extended source (behind him/herself) being reflected from two mirrors separated by this distance t (see Figure 2). In this fictitious construction, the mirror nearest to the eye appears to both let the light travelling to the far mirror through unimpeded and also to reflect it!

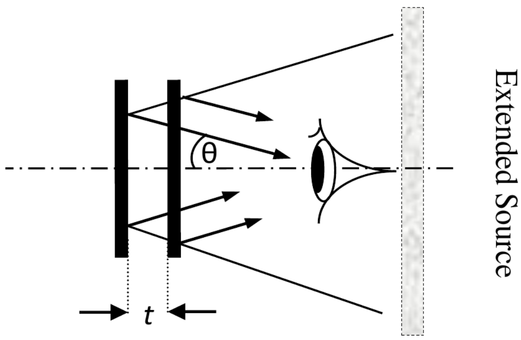


Figure 2: Simplified model of a Michelson interferometer.

We can use this construction to see what happens if we choose either to tilt slightly one of the mirrors or to leave it correctly aligned (see Figure 3). In both cases we imagine light coming from an extended source so that the angle θ of the incoming rays will vary. Now rays of wavelength λ reinforce each other at angles which make the optical path difference between consecutive rays an integral number of wavelengths, so that constructive interference will only occur for specific values of θ. **The cylindrical symmetry of the situation in Figure 3a suggests that the so-called Haidinger fringes will appear to be circular**. The cylindrical symmetry is broken by tilting one mirror, which produces straighter Fizeau-like fringes although with poor visibility compared to a point source.

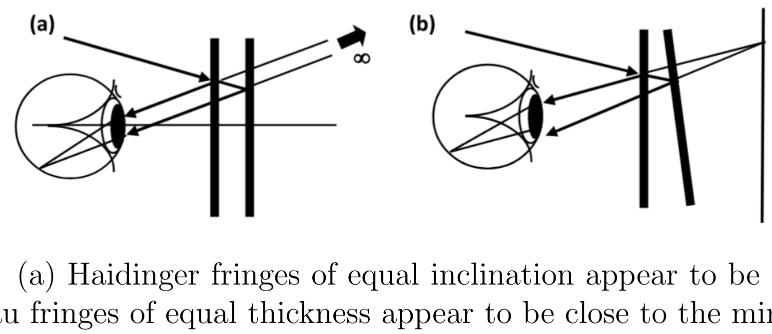


Figure 3: (a) Haidinger fringes of equal inclination appear to be at infinity. (b) Fizeau fringes of equal thickness appear to be close to the mirrors.

Task 1 - Pre-lab task
The equation governing the angle θ in Figure 3 is:

$$2t\cos\theta = m\lambda \tag{1}$$

In this equation t is the separation and m is known as the order of interference and it is assumed that the refractive index of the medium is 1. Derive this equation in your lab-book.

So, for an extended monochromatic light source, a pattern of concentric circular fringes can be observed, with their bright maxima conforming to integral values of m in equation 1.

2.2.2 Flat Fringes Produced by Plane Waves

In many situations, a collimated laser beam can be approximated by a plane wave, despite it usually having a Gaussian transverse intensity distribution. A very simple form of interference pattern is obtained when two plane waves intersect at an angle, as shown in Figure 4.

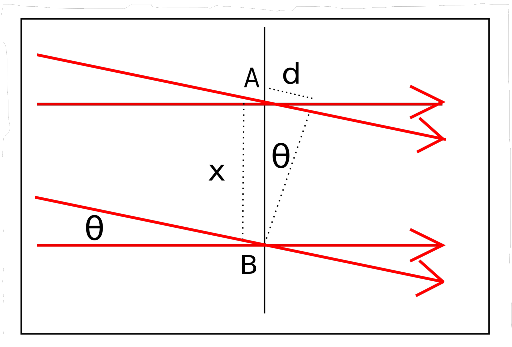


Figure 4: Geometry for interference of two plane waves.

One wave is travelling horizontally, and the other is travelling downwards at an angle θ to the first wave. This is a good approximation to a Michelson interferometer with a collimated laser as source and with a "misaligned" mirror. Assuming the two waves are in phase at point B, then the relative phase will change along the x-axis. By writing the phase difference at point A and imposing the interference condition, it can be shown that the resulting interference pattern is sinusoidal along x and composed of bright and dark fringes with a separation between maxima given by

$$\Lambda = \frac{\lambda}{\sin\theta}, \tag{2}$$

where Λ is known as the fringe spacing. The fringe spacing increases with wavelength and decreases with the angle θ, so the larger the misalignment, the denser the fringe pattern; fringes are observed wherever the two waves overlap. These results are summarised in Figure 5, where we see that this geometry effectively corresponds to a wavelength magnifier.

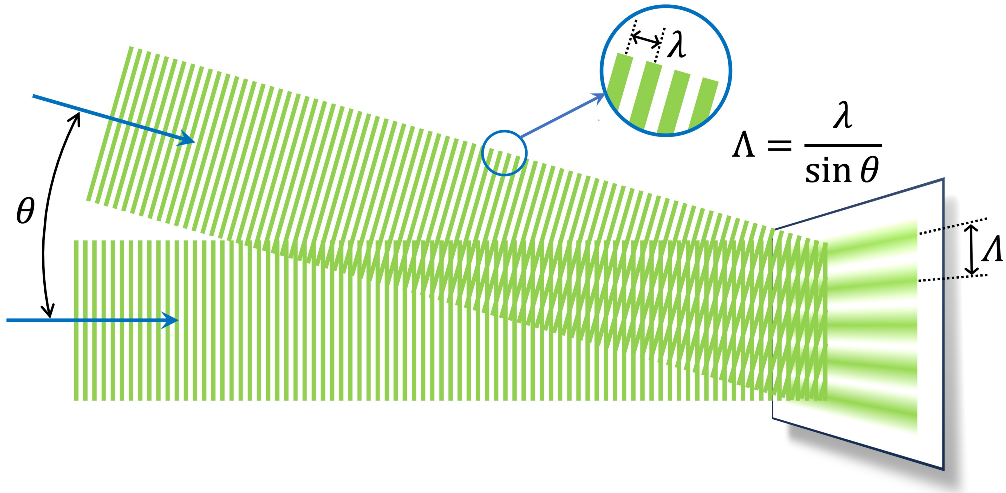


Figure 5: Interference pattern produced by two overlapping plane waves, as seen on a screen. For sufficiently small crossing angles, the fringes become macroscopic and can be seen with the naked eye.

2.2.3 Circular Fringes Produced by Spherical Waves

Another important situation occurs when the source is a spherical wave, which can be a good approximation to a diverging laser beam. In this scenario, when an interferometer is **perfectly aligned**, it will produce concentric fringes, as shown in Figure 6. The number and density of fringes decreases for decreasing path difference between the two arms, and for near zero path difference we see essentially a single fringe over the full beam. **Can you explain, using simple geometrical arguments, why this happens?** This is a very important configuration that we will use throughout the work to precisely align the interferometer both geometrically (parallelism between the two mirrors) and when looking for the point of zero path difference (the so-called null point), which plays a key role when measuring sources with broad spectral content and correspondingly short coherence length.

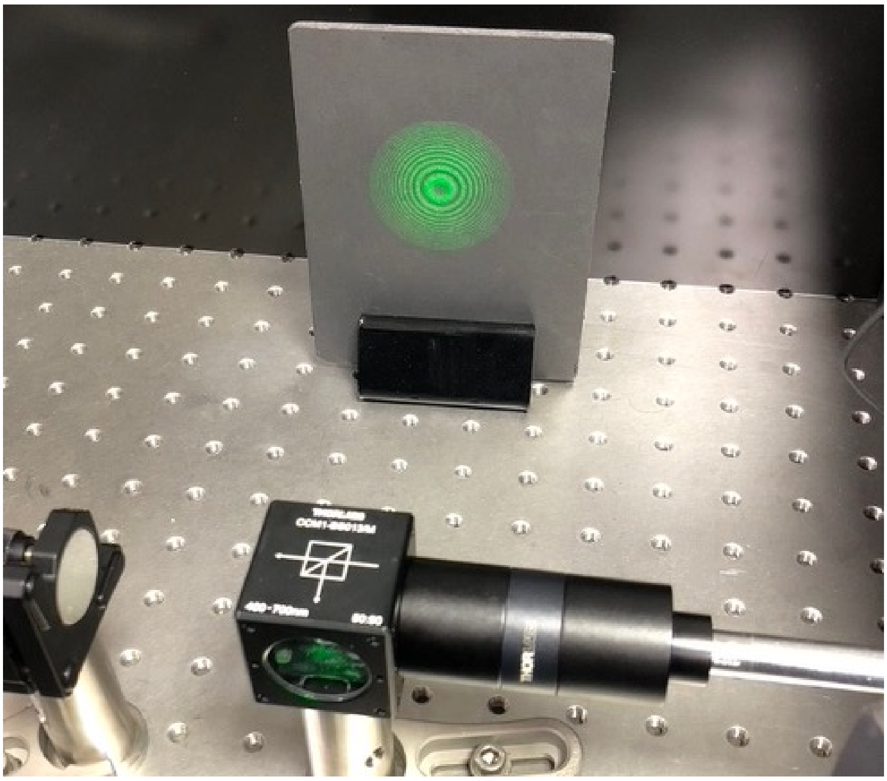


Figure 6: Circular fringe pattern produced on a screen by a Michelson interferometer with a diverging laser beam as source. **The presence of numerous fringes in the pattern indicates a significant path difference between the two arms of the interferometer.** In other words, the system is still far from the null point.

2.3 Using the Michelson Interferometer as a Spectrometer

We now return to considering the simpler case of sending a collimated beam (plane waves) into the input port and ask how the instrument can be used as a spectrometer. To do this we scan the position of one of the mirrors about the point where $t = 0$ (the null point) hence changing the path length of one of the beams.

The output of the interferometer can and should be inspected by eye. For a single monochromatic wave the output is just a series of bright and dark fringes. By measuring the intensity of light using an electronic detector for each position of the mirror, we record an **interferogram**.

In frequency space, a monochromatic wave is a delta function. What happens if the light we send into the instrument consists of two distinct frequencies (see Figure 7)? The sequence of bright and dark fringes (interferogram) is modulated and the separation between the nulls in the interferogram is related to the separation of the two frequencies in frequency space. The relationship is a reciprocal one − the closer the two frequencies are to each other, the further separated are the nulls in the interferogram. To see how this occurs consider Figure 8.

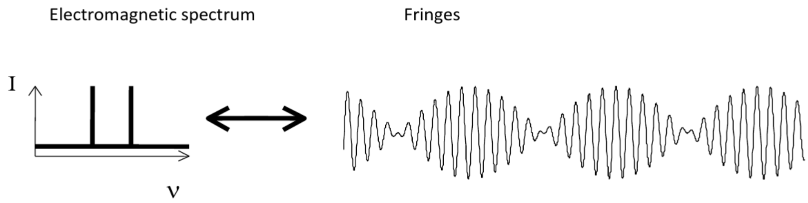


Figure 7: A simple electromagnetic spectrum and its resulting interferogram.

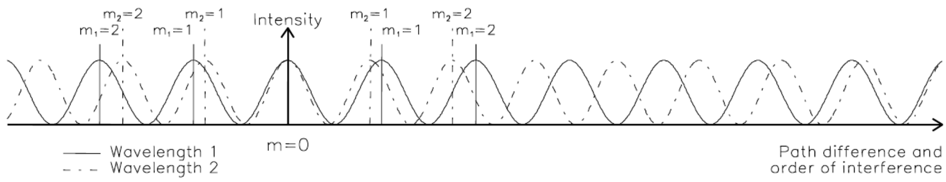


Figure 8: As t is scanned, two waves of different λ become out of phase, leading to a diminution of the contrast of the fringes. In due course, the waves re-phase and the contrast is restored. The pattern repeats as t is scanned further.

We imagine initially setting up the interferometer with exactly equal arm lengths ($m = 0$). Then, we monitor the output intensity as we scan one mirror. If we were to 'filter out' one wavelength we would observe the usual sinusoidal fringes (i.e. either the solid line or the dashed one in Fig. 8). The actual output seen is the sum of the two intensity distributions shown.

Notice in Figure 8 that the length of the fringe train shown is such that as one moves away from the zero path difference point ($m = 0$), the fringes formed by the longer of the two wavelengths are almost beginning to 'catch up' with the fringes formed by the shorter wavelength. When that happens (when the two fringe patterns are in phase) the overall fringe pattern is more or less the same as it is at zero order; but this is only true at that point when there are only two wavelengths. If there are other wavelengths present, their fringe patterns will not be in phase at that point.

Task 2 - Pre-lab task

Note that when there are only two wavelengths, the fringe intensity contrast will be a minimum when the pattern from one is exactly out of phase with the pattern from the other. In the case of plane waves (i.e. when $\cos\theta = 1$), the required condition is:

$$2nt = m_1\lambda_1 = (m_1 + 1/2)\lambda_2 \tag{3}$$

where $\lambda_1 > \lambda_2$ and t is the path difference between a maximum and a minimum in the interferogram.

Show that for n=1 we have:

$$(\lambda_1 - \lambda_2) = \lambda_2\lambda_1/4t \simeq \lambda^2/4t \tag{4}$$

if $(\lambda_1 - \lambda_2)$ is small. How small does the difference in wavelengths have to be for this relation to hold? **Can you explain the practical applications of Eq. (4) in the context of an interferogram produced by two different wavelengths?**

A rigorous treatment for a source with an arbitrary spectrum involves the mathematics of Fourier Transforms, which you have covered in your first-year course. We will explore the fact that **the Fourier transform of the interferogram is the power spectrum of the source**, which can be seen as an application of the (even more general) Wiener-Khinchin theorem.

The discrete spectral lines emitted by spectral lamps are approximately Gaussian in shape, i.e. $I(\nu) \propto \exp[-\frac{(\nu-\nu_0)^2}{2\sigma^2}]$, where ν_0 is the line centre and σ is the width. **Discuss with your demonstrator why this should be the case.** Sources with broadband and continuous spectra, like an LED, can sometimes be approximated by a Gaussian. An interesting result of Fourier theory is that a Gaussian spectral feature leads to a Gaussian temporal feature (interferogram) – see Figure 9.

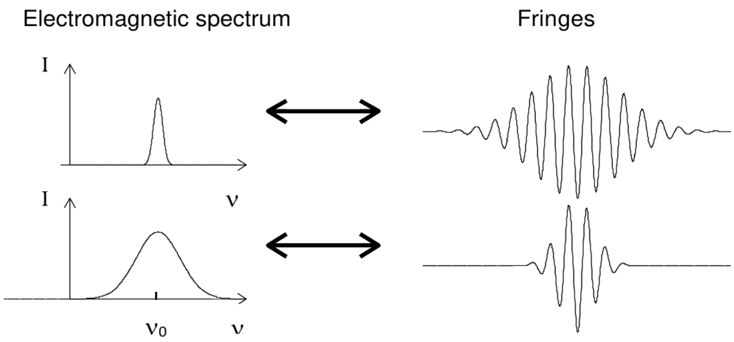


Figure 9: A narrow Gaussian spectral line leads to a wider Gaussian interferogram. The broader the spectral line the narrower the interferogram.

A key relationship exists that describes how the width L of an interferogram is related to the spectral width $\Delta\nu$, assuming a Gaussian spectrum and widths defined by the full width at half maximum (FWHM). This relationship is given by

$$\Delta\nu \times L = \frac{2\ln 2}{\pi} c \approx 0.441c. \tag{5}$$

To turn this into wavelength, you can use

$$\Delta\nu = \frac{c}{\lambda^2}\Delta\lambda. \tag{6}$$

In these equations, the coherence length essentially tells us over what path difference the interference fringes are effectively visible. Remember, this expression is derived under the assumption of a Gaussian spectral profile and uses a factor that is specific for FWHM measurements (0.441). Different factors would be used if other measures of width were used (like the standard deviation, etc.).

2.4 Some useful definitions

In this subsection, we have provided some definitions of terms that come up frequently and you need to be comfortable with. For a more complete collection of the terms used in this document and their definitions, please see Appendix A for a full glossary of terms.

Spectral line: Narrow spectral features are called lines because of the shape they make on a screen when using a conventional spectrometer (e.g. grating spectrometer) i.e. the lines are an image of the entrance slit.

Spectral width: The spectral width of a source is a measure of the range of frequencies emitted by the source or, when referring to a single spectral line, the width of that line.

Spectral width of a filter: The spectral width of a filter, often called its "bandwidth", is a measure of the range of frequencies passed by the filter.

Coherence length: The spectral quality of a light source is often described by quoting its 'coherence length'. Roughly speaking, for a given light source, this is a measure of the distance over which one arm of a Michelson interferometer can be scanned before the interferogram contrast becomes poor. The longer the coherence length, the closer the wave is to being perfect sinusoidal. Quantitatively, the coherence length can be found by calculating the width of your interferogram. You might want to define the width as the full width at half maximum (FWHM), for example, or you could fit a Gaussian to the envelope of your interferogram and define the width as two times the standard deviation of that Gaussian. It doesn't matter exactly how you define coherence length, but it is very important that however you define coherence length and spectral width of your source, the correct numerical factor is used in the relationship between the two widths.

Fourier Transform Spectrometer: When a Michelson interferometer is used to perform spectroscopy it is called a Fourier Transform Spectrometer (FTS).

3 Simulating the Michelson Interferometer

3.1 Why we do simulations

Simulations of a physical system can be considered to be models of the system with various degrees of sophistication. Their purposes can include:

1. developing an understanding of the physical system by varying parameters and inspecting the expected output

2. optimising the time taken in the lab collecting data by testing which sets of parameters should give you "good" data

3. assessing which assumptions are valid by comparing the simulation output with the experimental measurements

Initially, our purpose is the first of the above, however you may find the simulations useful when planning your data collection and writing up your report to check your assumptions. You will simulate the interferograms of a source whose spectrum you will specify, and then reconstruct the spectrum from the simulated interferogram - using the same analysis methods you will do with the experimental data. You will gain intuition for what the interferogram of a source with a particular spectrum looks like, and you will be able to adjust further parameters for the simulated interferogram, such as the density of data points and the scan range, to see how this affects the quality of the reconstructed spectrum (and hence the quality of the simulation itself).

3.2 The simulation code

Start by downloading the code from the Interferometry GitHub repository: github.com/ImperialCollegeLondon/PhysicsYear2Labs-Interferometry. You will need a github account associated with your Imperial email address - instructions are available on the module Blackboard site: Interferometry page. You might want to download the whole folder now, but for the following section we will only be using `Simulation.py`.

When you build and run your Michelson interferometer you will move mirror (M1) at a constant number of steps per second and sample the intensity of light at the detector. M1 is driven by a stepper motor. Imagine that this motor has a minimum step of 30 nm, which corresponds to a change in t of 60 nm - (make sure you understand why). These are actually the specifications of the previous stepper motor used on this experiment, but they are as good as any for the purpose of the simulation. This should result in an interferogram which evenly samples in t.

In your simulation you will set up an array of points corresponding to the different t values (in the example code below this is the variable x). You will then set the intensity at each of these t values to be zero, meaning there is no light in the system. The intensity corresponds to the variable y in the example code below. So, the code will look something like this:

```
# Describe the global calibration used
metres_per_microstep = 1e-11

# Now set up the experiment that you want to do
sampling_freq = 50 #Hz
motor_speed = 30000 # musteps per second
```

```
start_position = -10000000 # musteps
end_position = -start_position # musteps

# set up the x-grid as seen on the interferogram
dsamp= motor_speed/sampling_freq # distance in musteps
                                 between samples
nsamp= int((end_position-start_position)/dsamp) # number of
                                 samples that you will take (
                                 set in the software)

# set up the number of modes to use under the spectral
                                 components
nmodes = 50

# construct the x-grid of the interferogram
# include factor of 2 to properly simulate path difference
x= np.linspace(start_position,end_position,nsamp) * 2.0*
                                 metres_per_microstep
# and set the y-values to zeros
y= np.zeros(len(x)) #setting the array that will contain your
                                  results
```

So now we have an interferometer with no light going through our array of intensities is full of zeros. The next stage is to add a light source. We have provided two functions that can add light sources: one that simulates a Gaussian light source and another that simulates a "top hat" or square light source.

An infinitely narrow line would give a sinusoidal interferogram that would go on forever. These functions approximate a source of finite width by a series of infinitesimally narrow lines. Figure 10 shows a Gaussian spectrum with a mean $\lambda = 565\,\mathrm{nm}$ and width $\sigma = 2\,\mathrm{nm}$ being approximated by 50 infinitesimally narrow lines (over 5σ).

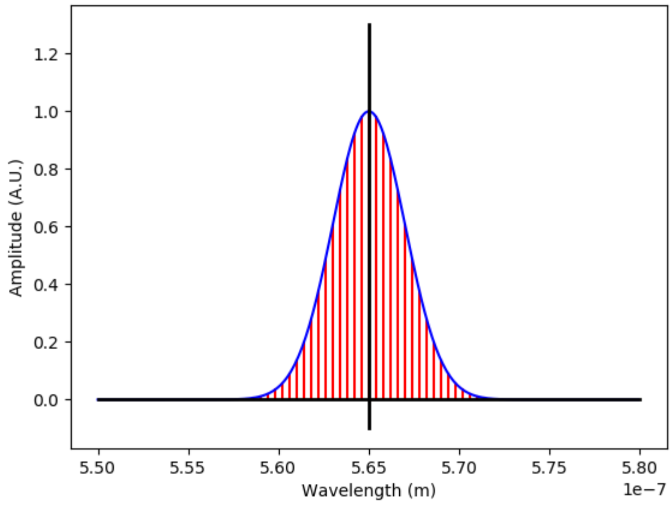


Figure 10: A Gaussian spectrum of finite width can be approximated by a series of (in this case 50) infinitesimally narrow lines (over 5σ).

This approach helps us understand that the interferogram is a Fourier transform of the original spectrum - **can you explain why?** However, we are sampling at discrete intervals rather than through a continuous integral and this can introduce non-physical effects into your simulated interferograms.

The function that can add a light source with a Gaussian spectrum to your interferogram is:

```
def add_gaussian(x,y,wl,amp,sigma,nmodes):

    This function adds the effect of a Gaussian line or
                                   spectrum to the
                                   interferogram.
    It does this by assuming that each Gaussian is made up of
                                    lots of discrete delta
                                   functions
    and calculates to +/- 5 sigma
    Inputs:
    x is the mirror separation in the interferometer
    y is the amplitude of the interferogram (may start at
                                   zero or add to existing)
    wl is the wavelength
    amp is the amplitude of the Gaussian
    sigma is the standard deviation (width) of the Gaussian
    nmodes is the number of discrete modes used
```

```
    nsigma=5 # the number of std devs over which the
                                    amplitude is calculated
                                    before cutting off
    amplitude=(amp*calc_gaussian_amp(nsigma,nmodes))

    amplitude=amp*amplitude/sum(amplitude)
    wl_step=nsigma*2.0*sigma/nmodes
    # construct the interferogram from the individual modes
    for i in range(len(amplitude)):
        wavelength=wl-nsigma*sigma+i*wl_step
        y=y+amplitude[i]*np.sin(2.0*np.pi*x/wavelength) +
                                        amplitude[i]
    return y
```

The function that can add a square spectrum light source is:

```
def add_square(x,y,start,amp,width,nmodes):

    This function adds the effect of a square (top-hat)
                                    spectrum to the
                                    interferogram.
    Inputs:
    x is the mirror separation separation in the
                                    interferometer
    y is the amplitude of the interferogram (may start at
                                    zero or add to existing)
    start is the wavelength to start the square from
    width is the width of the square (so it goes from
                                    wavelengths start:start+
                                    width)
    amp is the amplitude
    nmodes is the number of discrete modes used

    step=width/(nmodes-1)
    amplitude=amp/nmodes
    for i in range(nmodes):
        # as we know the amplitude is constant we don't need
                                        a separate function to
                                         calculate it
        wavelength=start+i*step
        y=y+amplitude*np.sin(np.pi*2.*x/wavelength) +
                                        amplitude
    return y
```

The amplitude (amp) is arbitrary in scale and only meaningful if you have two or more lines with different intensities. Hopefully, the descriptions in the code make the other calling arguments pretty clear; if they are not then ask a demonstrator.

We have already said that the interferogram is the Fourier transform of the original spectrum. However, this is not the spectrum in terms of wavelength, λ, but rather wavenumber, $\tilde{\nu} = \frac{1}{\lambda}$ so some manipulation is required to turn this into a wavelength spectrum. Here is the code:

```
# take a Fourier transform
yf=spf.fft(y)
xf=spf.fftfreq(nsamp) # setting the correct x-axis for the
                               Fourier transform.
                               Oscillations/step

#now some shifts to make plotting easier
xf=spf.fftshift(xf)
yf=spf.fftshift(yf)


# Now try to reconstruct the original wavelength spectrum
# only take the positive part of the FT
# need to go from oscillations per step to steps per
                               oscillation
# times by the step size
xx=xf[int(len(xf)/2+1):len(xf)]

distance = x[1:]-x[:-1]
repx = distance.mean()/xx

pl.figure(3)
pl.plot(repx,abs(yf[int(len(xf)/2+1):len(xf)]))
pl.xlabel( Wavelength (m) )
pl.ylabel( Amplitude )
pl.xlim(300e-9,800e-9)
pl.savefig( figures/sim_spectrum.png )
pl.show()
```

Don't worry if parts of the code don't make sense to you yet. You will be able to get to grips with it when you use it in Task 3.

Task 3 - Pre-lab task
When performing these tasks you should concentrate on their conceptual aspects and use numbers that are approximately correct rather than worrying about the detailed numbers.

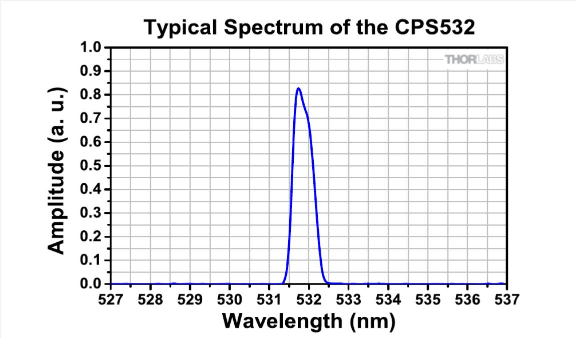


Figure 11: Spectrum of Thorlabs CPS532 green laser, as given in the manufacturer's website. **Or is it?** *Important:* This spectrum was measured using a grating spectrometer with a resolution of the order of 1 nm, and this is the width seen above. Using Eqs. (5) and (6) it is easy to see that such a broad linewidth would result in a coherence length of less than 125 micrometres, in strong disagreement with experiment. The true spectrum of the laser is much narrower than what is shown above and cannot be resolved by the grating spectrometer.

(a) Within the possible scan range of the interferometer you will be using, the laser behaves very much like an ideal single frequency source. Using this information, simulate an interferogram of the laser.

(b) Experience has shown that some of the lasers in the lab are in fact not single frequency. In some of the lasers, the emission is actually made of two separate lines (these are in fact laser modes) which are very close together. Start by simulating this situation with two lines of the same amplitude and width, separated by about 0.7 nm.

Once you have done that, describe how the interferogram changes as you systematically vary the widths, then the separation, and then the relative amplitude of these lines.

Optional: If you like, you can also try adding a third line, or more.

(c) Experiment with different distances between data points and different lengths of run in the generated interferogram to see what difference it makes to your reconstructed spectrum. Hint: Research the Nyquist-Shannon sampling theorem to understand your results.

4 Building and Aligning the Interferometer

In this section, you will construct your interferometer and align it. Before proceeding, here are a few notes:

- The mirrors are front surfaced. You should avoid touching them or clean them after touching them.
- Do not unscrew or move the linear translation base (containing the motor, micrometer, lever, and mounted mirror).
- Ensure that all optical components are well secured in their mounts, without play or rattle, and the mounts are properly screwed into their metal pillars.

4.1 The Importance of Alignment

Even though the preceding analysis and the data processing you will be doing only consider the temporal and spectral characteristics of the source under study, the spatial coherence of the source will dictate how stringent the alignment must be in order to produce good quality interference.

For sources with low spatial coherence, like the spectral lamp, it is vital to ensure the interferometer is very well aligned geometrically, otherwise you will not observe any interference or its quality will be strongly impaired. Since each point of the lamp emits light independently of the other points, no fixed phase relationship exists between light emitted by two different points, so a given portion of the beam can only interfere with a replica of itself. In other words, you must achieve a near-perfect overlap between the two beams of the interferometer. Furthermore, if the source has also low temporal coherence (and hence a short coherence length) you can only observe interference over a very small scan region around the point of zero path length. The good news is that these two alignments (geometry and path difference) can be achieved to a high degree by using the laser (which is highly coherent) prior to replacing it with another source.

In the first formative lab session, you will build and align a basic interferometer and focus on the spatial characteristics of the resulting fringe patterns.

Task 4

Start off by identifying each of the components you have been given. Use the list of components in the appendix to help you.

Then start constructing an interferometer using the relevant parts. You will be aligning the various elements as you mount them into place.

As is common in optical setups, all beams of light in our interferometer need to lie in the same horizontal plane at a fixed height. Thankfully, all the optical components you will be using are of the same, fixed height - so you do not need to worry about this.

You will now mount and align the various components to obtain a Michelson interferometer similar to the schematic in Fig. 1.

(a) Building the basic interferometer with the laser

- Mount the laser in the beamsplitter mount with the help of a tube spacer, noting the orientation of the beamsplitter (a schematic of its operation is engraved on the top of the mount). This ensures the correct alignment between laser and beamsplitter, with the resulting assembly producing two orthogonal beams. Note: do not overtighten the laser in the beamsplitter mount, otherwise you may misalign the interferometer later when changing the source or installing a lens.

- Place the beamsplitter and laser assembly in front of the mirror on the linear translation stage and orient it such that the beam (you can choose either the transmitted or the reflected beam) hits the centre of the mirror and all beam paths are perpendicular. Then clamp the assembly down with a mounting fork.

- Install the kinematic mirror mount so that the distance between it and the beamsplitter is equal to the distance between the beamsplitter and the linear translation stage mirror. Orient the mount so that the beam hits the mirror in the centre and the reflection goes back into the beamsplitter. Then clamp it down. Your setup should be similar or equivalent to the example in Figure 12(a).

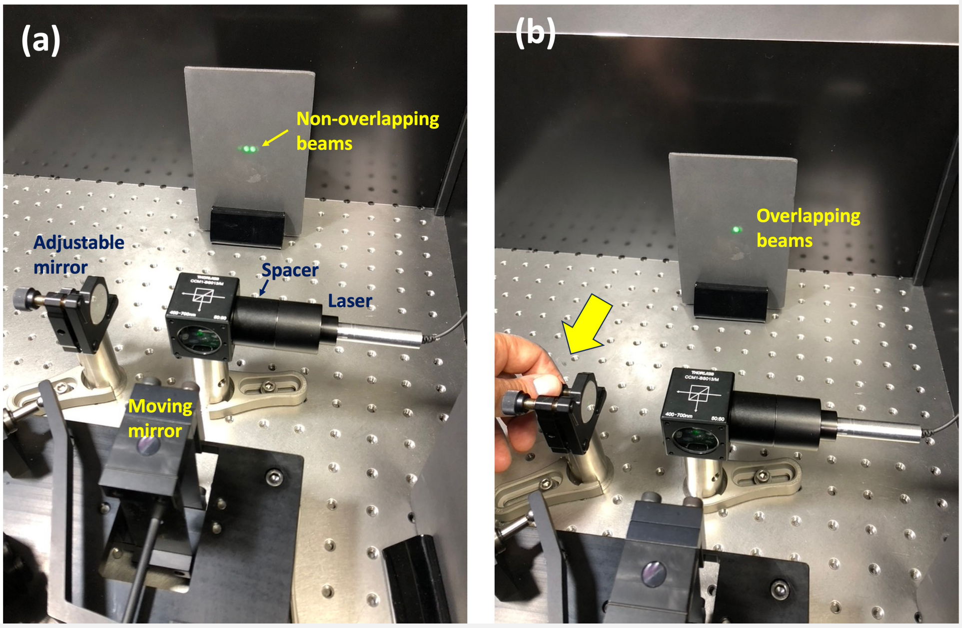


Figure 12: Example of a basic interferometer setup with a green laser as source: (a) prior to adjusting the mirror; (b) after adjusting the mirror to overlap the beams from the two arms on a screen.

- Now you will correctly align the kinematic mirror. Use the adjustable knobs to tilt the mirror so that the two laser spots are directly on top of each other at the output plane, as shown in Figure 12(b). You might want to place a black card at the output plane so that you can see the spots more clearly.

(b) Observing Fizeau fringes

- You now have the two spots from the laser beam directly on top of each other on the output plane (the two spots each come from one of the arms of the interferometer). There is interference happening. To see the interference pattern, place a lens in front of the output plane to expand it. You can do this by screwing a lens onto the side of the beamsplitter facing the output plane as shown in Figure 13(a).

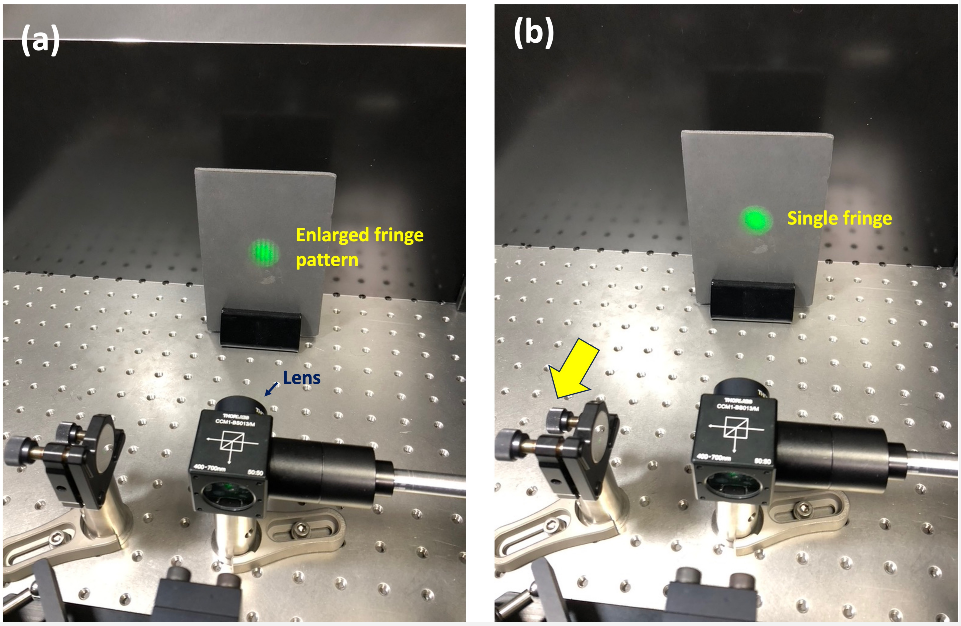


Figure 13: Fizeau fringes expanded with a lens for easier observation.

- You should now see straight lines which are Fizeau fringes. Adjust the kinematic mirror to change the orientation of the fringes. Obtain both vertical and horizontal fringes. Obtain a single fringe like in Figure 13(b). **What does this single fringe mean?** Explain the observed dependence of fringe spacing and orientation on the mirror tilt.

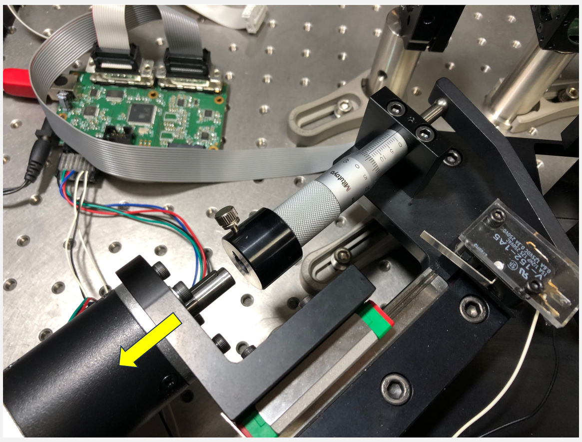
- Remove the expanding lens in front of the output plane and install it directly in front of the laser to obtain curved Fizeau fringes at the output of the interferometer. Adjust the kinematic mirror to see the effect on the fringes and to obtain a symmetric and well-centred pattern. Keep this lens in place for Task 5. You should obtain a pattern similar to that in Figure 6.

Task 5

(a) Manually moving the linear translation stage

- In this task, we will manually move the mirror on the linear translation stage, hence changing the path length difference between the two arms of the interferometer. We will see the effect this has on the interference pattern.

- Start by decoupling the micrometer screw from the motor (there is a retaining screw to loosen). If you are uncertain of how to do this, ask a demonstrator.



- Now move the micrometer screw by hand (you can go fast at first if necessary) and see the effect this has on the interference pattern. Try to find a range for which you have approximately a single fringe/ring, as shown in Figure 14(c). This will be very important for the remaining part of the work since in this situation the beam path difference should be near zero (the so called null point). Explain what you see as you move the mirror around that point. If you can't obtain a single fringe, this means the null point is still outside the full range of the screw, so the kinematic mirror will have to be moved closer to (or away from) the beam-splitter in order to correct this. But don't worry for now. This will not affect the following task where you will be taking data with the laser.

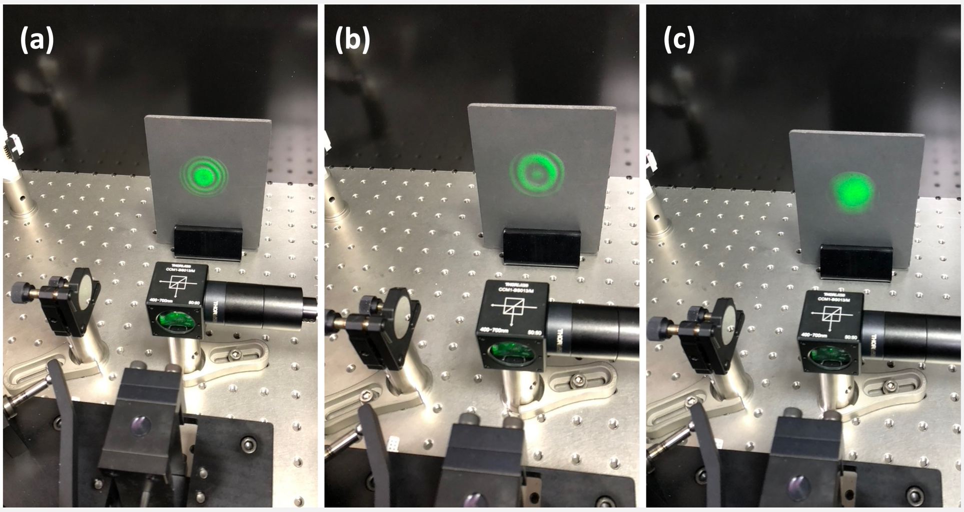


Figure 14: Curved Fizeau fringes for different positions of the micrometer screw. Note that a lens was used right after the laser to produce a diverging input beam.

(b) Observing Haidinger fringes

- Remove the lens that is directly in front of the laser, and replace it with the ground glass diffuser to obtain an extended source - this will give you Haidinger fringes. *Note:* fringes will look sharper (higher contrast) if the interferometer is set close to the null point. You may also see a small bright dot at the centre of the pattern; this is the specular transmission, which refers to the portion of the beam that the diffuser directly transmits without scattering.
- Adjust the mirror and micrometer screw to see the effect on the fringes.
- Insert a lens (try each of the available lenses) at the output plane of the interferometer and record how the interference pattern changes as you move a screen around the focal plane of the lens. Which position gives well-defined fringes? For weaker sources, using a lens at the output can also increase the amount of light sent into the photodetector used in the next tasks.

You are now ready for data collection. For data-taking, choose one of the configurations you did previously and give the reasons behind your choice.

5 Taking your first data and analysing it

Now you have reached the stage of taking your first data and examining it. First, install the photodetector at the output of the interferometer (see example in Figure 18) and connect it to the micro-controller board.

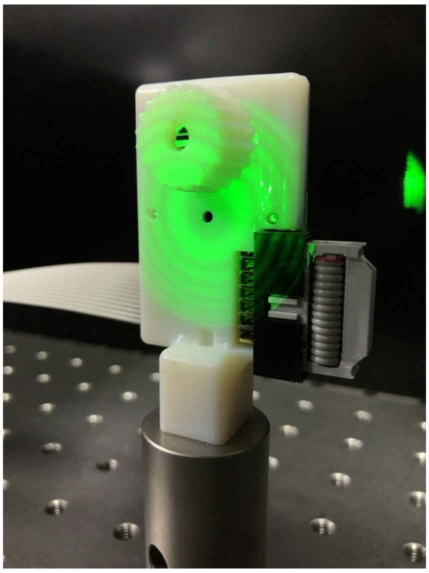


Figure 15: The photodetector placed at the output of the Michelson interferometer, with its entrance aperture centered with the interference pattern.

The photodetector is actually a photodiode attached to an amplifier with a variable gain, and then fed out through a 24-bit ADC. You can change the gain of the amplifier by adjusting the knob on the front of the detector. The maximum gain is when the arrow is pointing straight down, and gradually comes down as you turn it anti-clockwise. The photodiode is positioned below the gain knob where there is a small hole in the plastic body of the detector. By default, the detector samples the signal at a rate of 50 Hz. Once you have installed the photodetector, you are ready to take data. **You will be adjusting and optimising the gain as you make your first data collection run in the next step**. This should be done in real time, e.g. during a trial run, as you observe the signal being measured by the photodetector on the computer used for data acquisition. **The gain should be optimised for every source and configuration of the interferometer and is a vital parameter for measuring light with low intensity.**

How to take data

When you start taking data you will need to connect the micro controller board to the PC via a USB cable. This board can take data from two separate photodetectors and also controls the movement of the mirror on the stage.

The mirror on the stage is very finely displaced by a stepper motor through a series of mechanical reduction mechanisms. These have been designed as follows:

- Inside the stepper motor there are 200 steps for a complete revolution.
- Each step itself is made up of 256 μsteps.
- The drive shaft from the motor then drives a gear box which has a reduction ratio of 100:1.
- This in turn rotates a micrometer which requires two revolutions to move 1 mm.
- The micrometer then pushes a lever arm that moves the mirror and has a reduction ratio of 6.25:1.

Task 6
Based on these numbers, **estimate** the conversion factor from microsteps to nanometres of the motor and stage assembly. That is, how many nanometres is one microstep?

Note that the numbers above are not exact and your calculation will only provide an estimate of the actual conversion factor. You will be able to obtain a much more accurate value in Task 7 by measuring an interferogram of a narrowband source with a well known wavelength (e.g., the green laser) and by using the code `crossing_points.py`.

To take data for the experiment, you need to start the GUI control software "HermitX Interferometry" installed on the computer.

Figure 16: GUI control software for motor control and interferogram collection.

The options in the control software are:

- COM port: select the COM port associated with the control board. As long as there is power to your control board, then the COM port should be detected automatically. If not, then check connections and make sure the USB cable is attached to both the control board and to the PC.
- Connect: Click to connect to the control board. You should now see the measured signal from the two photodetectors (if physically connected) being displayed. This data is **not** being saved.
- Output folder: This will default to your OneDrive>>Documents directory. Select "Browse" to choose another location for datafiles to be saved to. We suggest you keep them in your OneDrive so you have easy access to them when you are away from the lab and you can share them directly with your lab partner.
- Show CH1(CH2) Full Scan: will display all of the data collected during this sampling run (downsampled to save memory). This is very useful

for seeing the overall shape of the interferogram, rather than the instantaneous data being collected over a finite time window. This option must be selected **before** beginning a scan otherwise the option will be greyed out whilst a scan is running.

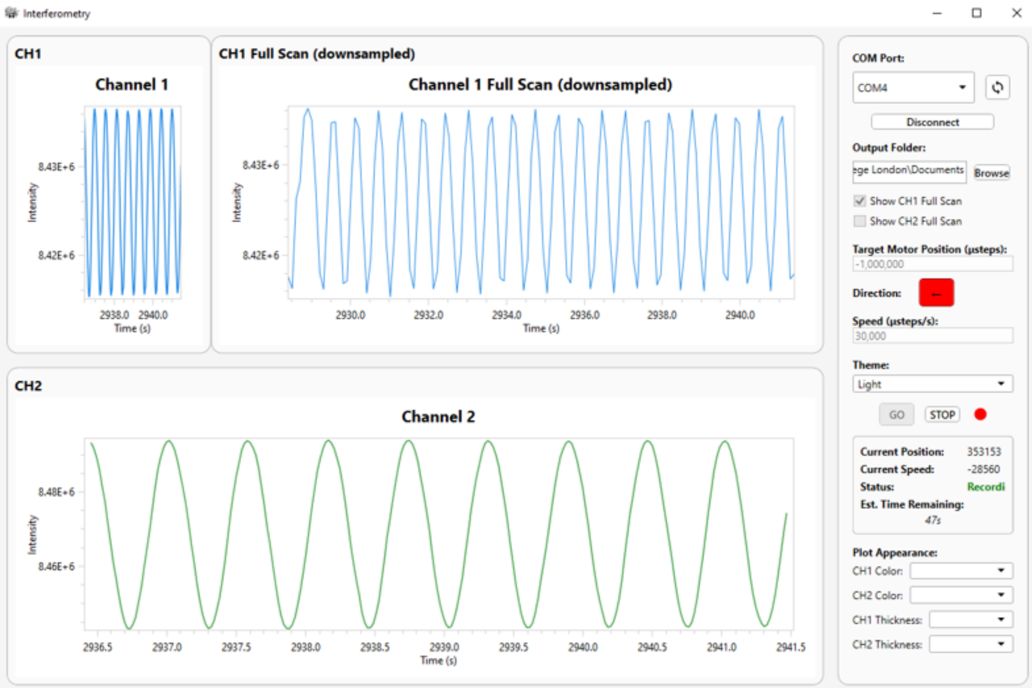


Figure 17: Full scan mode for Channel 1.

- The next three options dictate movement of the stepper motor:
  - Target Motor Position (μsteps): this is the position to which you want to move the stage in microsteps relative to the zero position. The zero position is the position of the motor when it is turned on and, therefore, is not retained from one session to the next.
  - Direction: click the arrow button to change the direction of travel. This can also be set by inputting positive or negative target motor positions.
  - Speed (μsteps/s): this is the nominal speed at which the stage will move in microsteps/second.
- Themes: You can select between light, dark and high contrast. During most of the sessions, you will want to use dark mode to avoid excessive light (and save your eyes some strain!)

Figure 18: Dark mode

- Go/stop: These buttons start/stop the scan and **saves** the data to the designated directory with a file name: "interferometry_data_date_time.txt" with the start date and time of the scan. Make sure you record which data file is associated with the experiment you were doing in your lab book.
- The box below the go and stop buttons gives information about the current scan. The most useful here is the estimated time remaining. This will give an approximate time left for your scan to complete.
- Finally, there are options for controlling the plot appearances.

A new file will be created each time you run a scan. Do not save data you want to keep on the local computer as it will be removed when you log out of the system. The output file is in tab-separated format. There are many columns in Output_data.txt.

- The 1st column is the reading on the 1st detector.
- The 2nd column is the reading on the 2nd detector.
- The 3rd is the number of seconds this epoch.

- The 4th is the number of microseconds this second.
- The 6th is where the stage thinks it is when the measurement was taken: the distance moved in microsteps.

A few important practical tips regarding data collection

- If you run into problems with the motor when taking data - e.g. after hitting the limiting switches, or if the stepper is not responding to move commands - these can usually be solved by unplugging/plugging in the USB cable from the computer, or by turning off then back on the switch of the mains socket used by the power supply of the micro controller board.
- You should place the cover lid over your setup when taking data, to minimise disturbances due to air flows, acoustic noise and ambient light. Alignment and optimisation should of course be done with the lid off.

Task 7
(a) Take an interferogram with the green laser by moving the mirror over a distance of about 0.1-0.2 mm. Decide the rate at which you move the mirror based on the expected value of the laser central wavelength and your understanding of the Nyquist-Shannon sampling theorem (how many data points do you want per fringe). Look at your data using quick_plot.py with the command:

```
python3 quick_plot.py my_data_file_name.txt
```

Note, all the Python scripts from the Git repository and the data file need to be in the same directory when using the above.

(b) Based on the distance between consecutive maxima in your interferogram, estimate the laser wavelength. Comment on the accuracy of your estimate. Is your laser emitting in a single longitudinal mode (frequency)? If not, what is the frequency spacing between modes?

(c) We can approach this same question from the opposite direction and take the wavelength of the laser as known to be 532.0 nm, then calculate the actual distance moved by each microstep of the motor.
There are a number of ways to do this. Perhaps one of the most direct is to remove the DC offset from the data that you have taken and then see the points where the line crosses the zero line. The program `crossing_points.py` does just this. It uses a high pass filter

to effectively make the signal AC coupled. This program will then analyse the distance between crossing points, assuming a central laser wavelength of 532.0 nm, and will give you the actual conversion factor in metres per microstep.

(d) While we have assumed the central wavelength of the laser to do this calibration, it is still possible to evaluate the obtained spectral width and compare with the expected width for a laser. Considering both, how do the spectral widths relate with the spectral resolution of the measurement? Based on the width of the measured interferogram, provide an upper limit for the actual spectral width of the laser.

(e) It is also possible to experimentally estimate the microsteps to nanometres conversion factor with the help of the micrometer screw in the moving arm. Explain how this can be done and determine the conversion factor and associated uncertainty.

6 Investigating LEDs

6.1 Simulating LEDs

You have already simulated a narrow linewidth laser. Now you will try simulating different light sources.

Later you will take data with a white LED, and place different filters in front of it. The width of the filters is ≈ 10 nm. However, the different filters have a different effect on the source spectrum: some result in an approximately Gaussian distribution of wavelengths, while others result in something much more like a "top hat" function. Therefore, in Simulation.py we have the function:

```
def add_square(x, y, start, amp, width, nmodes):
```

where x and y are the same as in the add_line function, start is the starting (lowest) wavelength of your top hat function, width is how wide your top hat is and nmodes is the number of modes that will be used in the approximation.

Task 8
(a) Use a Gaussian to simulate a white light source. Make reasonable guesses for the central wavelength and the width. Try varying the spectral width of the white source and see how this affects the width of the interferogram.

(b) Simulate a broad light source that is coming through a filter (i.e. assume that the light source is flat for the region that is allowed through the filter). Simulate the interferogram that you get if the resulting wavelength distribution is a Gaussian, and if it is a square function (remember that the Fourier transform of a square function is a sinc(x) function).

Try varying the width of the filter and see how this affects your interferograms.

6.2 Taking interferograms of LEDs

Now that you have performed simulations, it is time to take real data. However, first, you need to learn how to find the null point of the interferometer.

Task 9
In this task, you will find the null point of the interferometer. This is the position of the moving mirror for which the difference in path lengths between the two arms of the interferometer is zero. A few important points:

- The null point is very important because light sources with short coherence length (i.e., any broadband source, such as an LED) can only produce interference over a very small region of a few micrometres around the null point.
- Most broadband sources (such as LEDs) are spatially incoherent, so you must also guarantee that the beams from the two arms of the interferometer are collinear and perfectly superimposed at the detection plane. **This, as well as a very good estimate of the location of the null point, can be obtained by first setting up the interferometer with the green laser with an expanding beam in order to produce circular fringes, as done in Task 4(b)**.
- Should there be any misalignments with a corresponding loss of interference in the subsequent measurements (LEDs and Hg lamp), going back to the green laser is the quickest and easiest way to spot and correct misalignments.
- You may want to collimate your source by using a converging lens placed approximately one focal length away from the source, as done in Fig. 19. This should increase the amount of light going through the interferometer and reaching the detector.

In all measurements, always ensure that you can clearly observe interference on a screen by eye prior to using the detector. If you can't see interference with good contrast using your own detector (the eye), neither will the photodiode.

Procedure
Part 1 - produce circular Fizeau fringes and estimate the position of the null point

- Set up the interferometer with the green laser, the smaller lens tube (25 mm long) and a lens (choose which one) to expand the beam before the beamsplitter.

- Ensure the micrometre screw is near the middle of its range.
- Ensure the two arms have roughly the same length (e.g., by using a ruler).
- Adjust the tilt of the kinematic mirror mount to obtain concentric and symmetric circular fringes. This ensures good spatial overlap between the two beams in the interferometer.
- Look for the null point by adjusting the micrometre by hand (you can move it quickly in the beginning if you see a lot of fringes) until you see a single fringe; this is also the point where fringes reverse direction.
- If you cant reach this point within the range of the micrometre, recheck the arm distances and adjust the position of the fixed mirror if necessary.
- Once you have the approximate position of the null point, move the micrometre screw back (counterclockwise) by 1 mm (1 turn) or so. This way you will be sure to find the null point by moving the screw in the clockwise direction after swapping the laser with an LED.

Part 2 Finding the null point with an LED

- Replace the laser with an LED (white or blue). Be careful not to twist the beamsplitter out of place as you do this.
- Now, turn the screw slowly (up to 1 division every 3 seconds or so) and observe the screen. As you approach the null point, you will start to see interference. The position of maximum intensity and contrast is the null point - see Fig. 19 below. **Record this position as it will not change as long as you don't change the arms of the interferometer**. In practice, the null point will be within a small range determined by the coherence length of the source.
- Alternatively, you can scan the motor and record the interferogram. Just like in the manual method above, this will only work if the interferometer was sufficiently well aligned with the green laser to begin with.

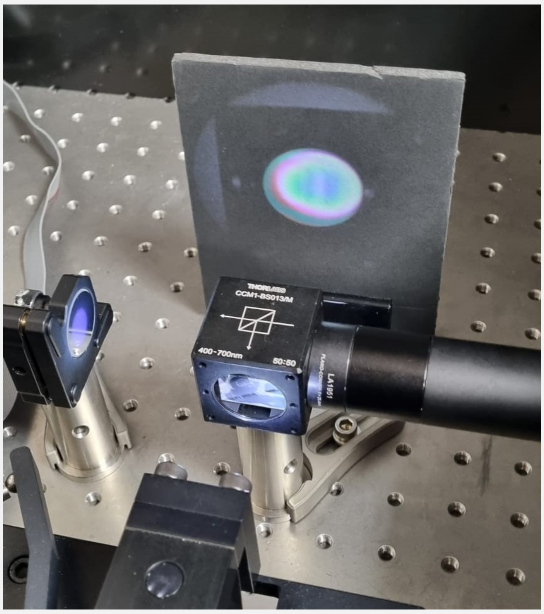


Figure 19: The colourful interference pattern obtained for a white LED near the null point. In this setup, a converging lens (attached to the beamplitter mount) and adequate spacer (threaded tube) are used for collimation.

- Now that you've found the null point with the LED, don't forget to optimise the geometric alignment for maximum spatial overlap, symmetry, and contrast of the resulting interference pattern. This is best done by looking directly at the interference pattern near the null point (see Figure 19). **Such alignment is vital for achieving high quality measurements in all subsequent tasks and must be rechecked and optimised prior to each measurement - and surely between lab sessions, as the components will likely misalign due to thermally induced mechanical changes and mechanical relaxation**.
- **Can't see anything?** Give it a another try over a broader range of the screw and/or install a filter at the output to increase the length of the interferogram and facilitate finding the null point. If you still can't see anything, temporarily replace the LED with the green laser to check/redo the alignment. It should only take a few minutes to do this and go back to the white LED.

You now know how to find the null point of the interferometer. Next, you will use this knowledge in taking interferograms of the white and blue LEDs, and then analyse your interferograms.

Task 10
(a) Take interferograms of the white LED, the blue LED, and the white LED with one of the filters. Don't forget to optimise the geometric alignment for each source and before each measurement. This is particularly important for spatially incoherent sources like the LEDs. You can quantify the quality of your alignment by looking at the fringe visibility of your interferogram (which is a measure of contrast). If necessary, it should be possible to further optimise the contrast by doing very slight tilt adjustments to the fixed mirror while looking at the measured signal during a test run.

(b) Estimate the coherence length of each source. Hint: Consider the width of the interferograms.

Use the coherence lengths to estimate the spectral width of each source. You may use the relationships in Equations (5) and (6).

Note: You should make sure you understand the idea and assumptions encapsulated by Equation (5), and it is a good exercise to derive it. Hint: You might want to research the general Fourier uncertainty principle.

(c) Using the interferogram data and the assumption that the distance between samples is constant (i.e. that the step size of the linear translation stage is constant over the whole measurement range), find the spectrum of each of these sources - you can use the code `apply_global_calibration.py` - and calculate their approximate central wavelength. Are the spectra as expected?

Note: **you can measure the spectra of your sources with the intensity-calibrated grating spectrometer available in the lab.** This apparatus and acquisition software are similar to what you already used in first year. Its resolution is low compared to what your Fourier-transform spectrometer can achieve, but it is still useful for providing reference spectra of the broadband sources as well as the approximate locations of the laser emission and the mercury spectral lines. Keep in mind that these lines are much narrower than the resolution of the spectrometer, so the spectral line shapes and widths that you see are dictated by the optical resolution (which is independent of pixel resolution) as well as optical aberrations of the grating spectrometer.

7 Investigating a Mercury Discharge Lamp

You have been given a Hg discharge lamp. You should be very careful with this as it is a very bright source with a lot of energy in the UV. This means that it can damage your eyes. **Avoid looking at it directly and you must use the safety goggles supplied**. You will make measurements of a green spectral line and the yellow doublet with this source. You may want to use a collimating lens to increase the intensity of the light going through the interferometer. You may also try to use the ground glass with this source. Please note that this lamp takes some time to warm up and attain full brightness, and this will show in your measurements if you don't wait long enough for the lamp to thermalise.

7.1 The Green Line

Task 11
In this task, you will investigate the mercury green line. You will want to use the green filter to isolate the green line in the mercury spectrum.

(a) The laser may have had instabilities but quantum mechanics means that the Hg spectral lines must be stable in normal conditions. Therefore, take a long (several mm) interferogram of the green line.

(b) Use this run and Equations (5) and (6) to estimate the width of this line.

(c) Investigate the stability and reproducibility of the movement of the stage. There are many ways to approach this, so be creative. You could start by looking at the regularity of the crossing points of the interferogram using `crossing_points.py`.

(d) Take an FFT of your interferogram to obtain the spectrum (you can use `apply_global_calibration.py`).

Note: In all parts of this task you should quantify your measurements, and remember that measurements are meaningless without errors.

7.2 The Yellow Doublet

Task 12
In this task, you will investigate the Hg yellow doublet. You may want to use the yellow filter to isolate the doublet.

(a) Take a long (several mm) interferogram of the Hg yellow doublet.

(b) Use the interferogram data alone to calculate:

i. The mean wavelength

ii. The separation of the lines in the doublet, using equation 4

iii. The widths of the lines, using equations 5 and 6

(c) Now, take the FFT of the interferogram. Does what you see make sense?

8 Correcting the Mercury Discharge Lamp Spectrum

This is section is challenging but also very rewarding. It shows you how to correct systematic errors using a known metrology source. It also shows you the power of using a Michelson interferometer for spectroscopy.

In this section you will use a known wavelength to correct for the motion of the stage. You will take two interferograms at the same time. You will then correct for the stage position by fitting a source of a known wavelength to correct the position of where the data were actually collected (i.e. fitting the position knowing the wavelength rather than the other way around). You will then use this to build a new interferogram for the unknown source. FFTs require the data to be evenly spaced (at least the algorithms you are using do), so you will then fit this new interferogram to produce a third interferogram that has evenly spaced points. We provide you with a code `apply_local_calibration.py` which will do this, although you may well wish to produce your own code using `apply_local_calibration.py` as a helpful guide.

8.1 Using the Green Line for Correction

Task 13
In this task, you will use the Hg green line to correct the measurement of the yellow doublet. You may want to use the yellow filter to isolate the yellow doublet.

You should follow the program `apply_local_calibration.py` for the steps in this analysis. This program should not be used as a black box but more as a template or starting point. There are many ways that you could make these corrections; what we suggest here is only one possible way.

(a) Reconfigure your apparatus using the second detector and another beam splitter so that the interferogram of the green line falls on one detector and the yellow doublet on the other.

(b) Take long interferograms (it is your choice how long).

(c) Using the green line (wavelength 546.07 nm[a]), correct for the positions where the data were taken.

The easiest way to do this is to use the crossing points as we did in `crossing_points.py` to set the absolute distance scale for each half wavelength. Then correct the position of the points in that half wavelength, and then move on to the next half wavelength building on the already corrected point. So the position of each point now is just

$$x_{corr} = x_{uncorr}^{init} + \frac{\lambda_{true}}{\lambda_{fit}}(x_{uncorr} - x_{uncorr}^{init}) \tag{7}$$

where x_{corr} is the new corrected position, x_{uncorr}^{init} is the initial uncorrected position at the start of the half wavelength being corrected, x_{uncorr} is the position of the current data point being corrected, while λ_{fit} and λ_{true} are the wavelengths from fitting to the measured interferogram and the literature value of the wavelength of the green emission line, respectively. By doing this we are essentially stretching or compressing the chunk of data that you have fitted to correct for irregularities in the stage's movement.

This now gives a corrected set of positions for where the data were actually taken. To use the FFT a “resampled” data set with even spaced points is needed. The simplest way of doing this is to fit a cubic spline to the corrected but now unevenly spaced data. In analysis.py, it shows you how to call the cubic spline function with regularly spaced points to do this.

(d) Now that you have a corrected interferogram with evenly spaced data points, take the FFT to get the spectrum. Does what you see make sense?

[a]These numbers can be found from spectroscopic databases kept by national laboratories. See if you can find this line in the NIST database and the appropriate primary data source for referencing it.

Task 14

In this task, you will use the Hg green line to correct the measurement of the entire Hg spectrum.

Repeat what you did for the previous task, but this time with the yellow filter removed. This should allow you to measure the entire Hg spectrum (or at least the part of it that is within the sensitivity range of the photodiode).

9 The Interferometry Lab Report

After the end of the four-week cycle, you will submit a four-page report based around one particular topic of your choice and cover the method, results, and conclusions of your studies. In the third week of the cycle, you should discuss with a demonstrator your report's topic. If you feel uncertain about what is required, keep asking questions! Then in the final week, you will have time to collect more data to help you answer the question that you will write your report on. It is even a good idea to start writing your report (e.g. introduction, methods) before the final week, as you will often realise that it would be good to collect data in a different/better way **through the process of writing!** Then you will have time to improve your work before submission.

A good way to decide what topic to write your report on is to consider what **choices** and **assumptions** you have made during the lab - in both data collection and analysis - and then investigating how that choice affects the measurements you have made. You should have a record of all the choices you have made in your lab book. A good report will provide evidence to support conclusions that can be made about either the physics of the system being investigated (the light sources) or the physics of the measurement apparatus being used (the interferometer). Below we provide you with a list of additional ideas that could be pursued for further investigation, though we welcome further ideas!

1. investigating properties of the mercury lamp
2. characterising the properties of the optical components in the physical set up and/or their impact on the measurements
3. investigating the impact of the acquisition parameters
4. investigating the impact of the calibration process

We deliberately have not detailed the 'properties' and 'impact' above as which properties/impact you might be interested in is up to you to decide. And it is also up to you how to quantify those properties/impact and how to account for any limitations in the methods used to measure said properties/impact.

You should also consider the assessment rubric and how best you might plan your data collection and presentation to meet the categories you are aiming for. There is always a trade off (in terms of the finite time available) in balancing the different descriptors in the rubric.

In the following subsection we provide some additional details on one method to investigate the calibration process further, as it pertains to reconfiguring the Michelson interferometer setup to use an external source for calibration. **Due to the limited supply of HeNe lasers, before you are allowed to use this equipment please discuss with a demonstrator why you want to use it**. You will need to have thought about your research question and how the HeNe laser is necessary for you to answer that question. There are many questions that can be answered without this equipment and, indeed, it may be a better use of your time to focus on collecting data from a setup you have already been using.

9.1 Using a HeNe Laser for Correction (Optional)

Here you use a red HeNe laser to correct the measurement of the Hg spectrum. This is an optional activity, and if you do it you will need extra apparatus. Ask your demonstrator to get this extra apparatus from the lab technician.

In research, Fourier transform spectrometers often have a metrology laser as a known calibration wavelength. You can add a laser to your instrument and use it as a general purpose spectrometer.

1. Using an extra beamsplitter, reconfigure your apparatus such that light from the red laser goes down the same optical path as the light from the mercury lamp.

2. Using the notch and bandpass filters, configure your detectors so that only light from the red laser falls on one detector and only light from the mercury lamp falls on the other.

   The filter that filters out the red laser light must be perpendicular to the incoming beam. If it is not then some light will leak through so make sure you align it carefully (using an optical tube might help).

3. Take long interferograms.

4. Correct the mercury spectrum in the same way as you did the yellow doublet previously (except obviously using the red HeNe laser wavelength of 632.8 nm rather than the mercury green line).

5. Take the Fourier transform of the entire mercury spectrum. Can you identify the features that you see?

Clearly, the results from this task should be similar to those you got using the green line as the correction wavelength, but what you have now is a general purpose instrument that can be used to analyse many different sorts of light sources. So, why not try some other light sources? For example, the green laser and the white LED, with and without filters.

A Glossary

coherence length The spectral quality of a light source is often described by quoting its ‘coherence length’. Roughly speaking, for a given light source, this is a measure of the distance over which one arm of a Michelson interferometer can be scanned before the interferogram contrast becomes poor.

collimated light Light that has parallel rays, and therefore will spread minimally as it propagates.

doublet In spectroscopy, a doublet refers to two features lying close in wavelength.

extended source An extended light source refers to a light source that has physical dimensions, meaning it occupies a certain area or volume, as opposed to being a point source. In other words, an extended source emits light over a larger spatial region.

Fourier transform spectrometer When a Michelson interferometer is used to perform spectroscopy, it is referred to as a Fourier transform spectrometer, abbreviated to FTS.

fast Fourier transform (FFT) An algorithm that computes the discrete Fourier transform of a sequence rapidly.

metrology The scientific study of measurement.

monochromatic light Light of a single constant frequency.

spatial coherence It essentially tells us about the consistency of phase across different spatial positions of a wavefront emanating from the light source, or the ability to obtain interference between different points of the same wavefront. Sources with low spatial coherence impose stringent alignment conditions on an interferometer in order to observe interference and to optimise its contrast.

spectral line Narrow spectral features are called ‘lines’ because of the shape they make on a screen when using a conventional spectrometer i.e. an image of the slit.

spectral width (of a filter) The spectral width of a filter, often called its “bandwidt”, is a measure of the range of frequencies passed by the filter.

spectral width (of a source) The spectral width of a source is a measure of the range of frequencies emitted by the source or, when referring to a single spectral line, the width of that line.

B Components and sources used in this lab

Table I: Optical Elements and Detector

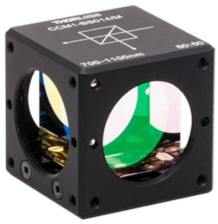
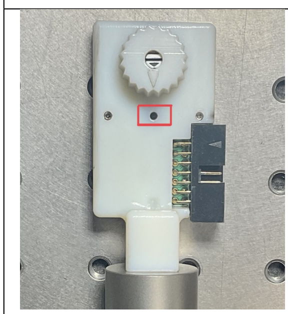
	Lens mount Supplier: Thorlabs P/N: LMR1/M	Used to securely locate lenses and other elements in an optical setup.
	Beam splitter Supplier: Thorlabs P/N: CCM1-BS013M	Splits a beam of light into a transmitted and reflected beam. Also can be used in reverse to combine two beams.
	Kinematic mirror mount Supplier: Thorlabs P/N: KM100	A mirror mount (with installed metal mirror) designed for precise alignment in optical systems.
	Photodetector Supplier: OSRAM/Imperial P/N: OSRAM SFH 2200	The detector is the OSRAM SFH 2200 inside a casing made by Imperial. The aperture is indicated by the red box. There are eight gain settings: the highest setting is when the arrow on the dial points vertically downwards, and the lower settings are accessed by rotating the dial anticlockwise.
	Lens tube Supplier: Thorlabs P/N: SM1L20	Used for mounting and spacing lenses and sources as appropriate.

Table II: Lenses

	Plano-convex lens, focal length 100.0 mm Supplier: Thorlabs P/N: LA1509-A	A plano-convex lens has one flat and one outward-curved surface with a focal length of 100.0 mm, commonly used in optical setups for focusing or collimating light.
	Plano-convex lens, focal length 25.4 mm Supplier: Thorlabs P/N: LA1951-A	One flat and one outward-curved surface with focal length 25.4 mm.

Table III: Filters

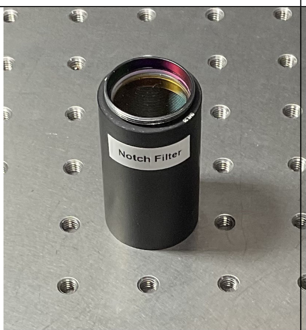
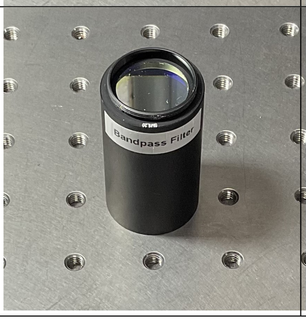
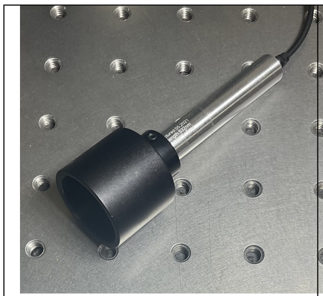
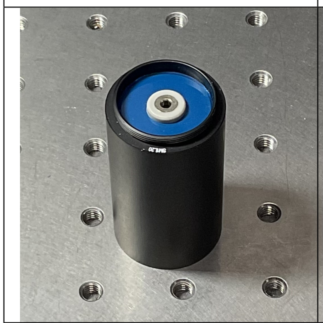
	Yellow filter Supplier: Thorlabs P/N: FB580-10	Allows only yellow light to pass through. See data sheet transmission spectrum for wavelength response.
	Green filter Supplier: Thorlabs P/N: FL543.5-10	Allows only green light to pass through. See data sheet transmission spectrum for wavelength response.
	Ground glass diffuser Supplier: Thorlabs P/N: DG10-1500-MD	Ground glass diffusers are designed to scatter light uniformly, commonly utilized to homogenize divergent beams and reduce speckle contrast in optical systems.
	Notch filter Supplier: Thorlabs P/N: NF633-25	Used for optional HeNe laser task. This filter will let most wavelengths in the mercury spectrum through, but will largely block out the HeNe laser. See data sheet transmission spectrum for wavelength response.
	Bandpass filter Supplier: Thorlabs P/N: FLH633-5	Used for optional HeNe laser task. This is a hard-coated bandpass filter. The point of this filter is to only let light from the HeNe laser through. See data sheet transmission spectrum for wavelength response.

Table IV: Tools and Other

	Ball screwdriver	Used to screw components to the optical table using the clamping forks. Make sure you screw components in firmly to ensure stability but not over-tightened.
	Magnetic beam ruler	Typically used to measure and set the height of optical components. It is magnetic, so it is easily attached to the optical table.
	Safety glasses x2	You must wear these when working with the mercury lamp, which emits UV radiation in addition to visible light. Prolonged exposure to UV can be harmful to the eyes: it can cause damage to the cornea, lens and other parts of the eye.
	Clamping fork x6	Designed to securely hold post holders and pedestal posts, which in turn hold optical components like mirrors and lenses. Make sure that the clamping fork is flush to the edges of the post holder or pedestal post you are trying to secure this ensures it wont move.

Table V: Light Sources

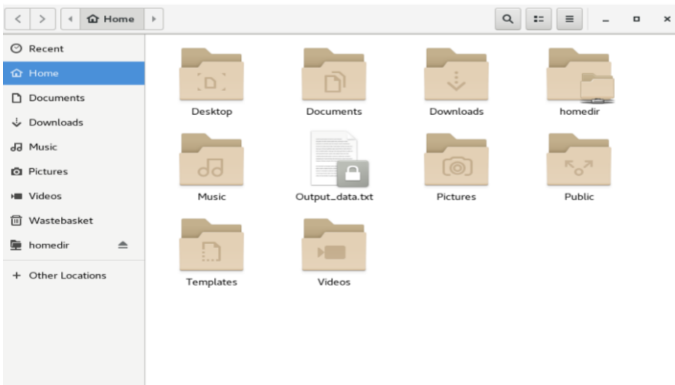
	Collimated laser Supplier: Thorlabs P/N: CPS532	You will use this green laser often for aligning the interferometer and roughly locating the null point. Do not point the laser towards your or any other persons eyes. A filter has been installed in the laser to reduce its intensity and make it safer.
	PenRay Mercury lamp Supplier: Analytik Jena/Imperial College Spec: Analytik Jena UVP Pen-Ray lamp P/N: 90-0012-01	The lamp is enclosed in an aluminium case built by Imperial. It can be rotated in its case to maximise the light output (after untightening the screw indicated in the red box). Do not overtighten this screw!
	Blue LED Supplier: OptoSupply/Imperial College P/N: OSUB5111P	A mounted light-emitting diode that emits blue light. This and the white LED below are mounted in a Thorlabs tube and share the same power supply as the green laser.
	White LED Supplier: OptoSupply/Imperial College P/N: OSPW5111P	A mounted light-emitting diode that emits white light.
	Frequency-stabilised He-Ne laser Supplier: Thorlabs P/N:	This is the red He-Ne laser used in the optional task. It is enclosed in a box built by Imperial and is fibre coupled to the outside, which also reduces its power to a safer level.

C Quick introduction to Linux

In this lab, you will be using computers that are running the Linux operating system. I know that most of you will not be familiar with Linux, however, it is the operating system in which most scientific computing is performed, so it is good that you become familiar with it. Linux is free, but the license is such that you can take the free distribution, modify it to suit whatever your purpose is, and then charge for what results. This is exactly what Apple does.

You should log on with your normal college username and password. You should then see a screen like this:

If you click on Home you will see the home directory that you have on this machine. It will look like this:



Just as on college computers running Windows, everything is transient except your college home directory. This is your OneDrive directory, which you can access via the web browser. So, anything that you want to keep needs to be stored in that directory.

In Linux you can do most things through the “clicky pointy” interface called a graphical user interface (GUI), but the command prompt (called the terminal in Linux) is a very powerful tool that you will need to use in this lab.

If you move your mouse pointer to the top left corner of your screen, you will see a selection of applications. You can choose to launch a terminal. In a terminal you can do many things. I was going to write a guide to Linux commands but there are so many on the web already, so you can look at any of:

- https://files.fosswire.com/2007/08/fwunixref.pdf
- https://www.dummies.com/computers/operating-systems/linux/common-linux-commands/
- https://www-uxsup.csx.cam.ac.uk/pub/doc/suse/suse9.0/userguide-9.0/ch24s04.html

The commands you will most commonly use are:

- ls (short for “list”) this lists the files in your current directory
- ls *tt* files in your current directory bearing ‘tt’ in their file name
- pwd (short for “print working directory”) tells you what directory you are in
- cd (short for “change directory”) changes the directory that you are in
- mv (short for “move”) renames or moves a file
- cp (short for “copy”) copies a file
- rm (short for “remove”) removes/deletes the file
- mkdir (short for “make directory”) creates a new directory

So, for example, if you are in your home directory on the computer and wanted to create a directory on your college home directory called interferometry, you would type:

```
mkdir homedir/interferometry
```

If you then wanted move to that directory you would type:

```
cd homedir/interferometry
```

If you just type "cd" you will move to your home directory on that computer. If you want rename a file or directory you would type:

```
mv old_name new_name
```

Similarly, if you want to copy a file:

```
cp original_file copy_file
```

All these commands have options associated with them that you can find either by using the "man" command (short for manual), or by researching it online.